Army Research Laboratory

Weather and Atmospheric Effects for Simulation

Volume 1: WAVES98 Suite Overview

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ARL-TR-1721-1 September 1998

Army Research Laboratory

Adelphi, MD 20783-1197

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Information Science and Technology Directorate

Abstract

The Weather and Atmospheric Effects for Simulation (WAVES) suite of models calculates and visualizes environmental effects due to natural clouds, haze, and fog. These models determine the illumination through multiple inhomogeneous cloud layers and the resulting radiance field. Other effects calculated with these models are forward scattering and optical turbulence. WAVES comprises BLIRB (the Boundary Layer Illumination and Radiative Balance model), ATMOS (a turbulence model), PixelMod (an image modifier), and VIEW (a viewing geometry model). Other models will be added to this suite in the future. A model being developed for the near future is 3DSMOKE, which is based on the EOSAEL (Electro-Optics Systems Atmospheric Effects Library) COMBIC (Combined Obscuration Model for Battlefield-Induced Contaminants) model. A ToolKit is being developed to aid in the viewing of input, output, and intermediate data within WAVES. This suite of models can simulate a scene or can be used to modify an image. This overview discusses the scope of this modeling suite, and maps the other documentation for the suite.

Preface

This report is one in a series of reports documenting the Weather and Atmospheric Visualization Effects for Simulation (WAVES) suite of models. WAVES predicts illumination and radiance information for a three-dimensional, variable atmosphere as a function of cloud type and optical density, including partly cloudy skies at visual and infrared wavelengths. WAVES was developed to augment atmospheric propagation calculations made by the Air Force models, Moderate Resolution Transmittance Model (MODTRAN) and Cloud Scene Simulation Model (CSSM). This series of Army Research Laboratory technical reports will include eight volumes, to be published individually (see sect. 5).

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1. Introduction

The Weather and Atmospheric Visualization Effects for Simulation (WAVES) suite of models predicts illumination and radiance information for a three-dimensional, variable atmosphere as a function of cloud type and optical density, including partly cloudy skies at visual and infrared wavelengths. WAVES also predicts electro-optic (EO) propagation effects for horizontal and slant paths through the natural atmosphere. Illumination and propagation effects are critical for accurate target acquisition and scene generation. The military has an interest in generating realistic imagery for a variety of weather conditions and displaying it on various computer systems for broad applications in Army wargames and simulations, information and planning, test and evaluation, training, and engineering and development. Augmenting realism in simulation models has driven Army Research Laboratory EO modeling researchers to develop a suite of models that compute the effects of the atmosphere on the propagation of electromagnetic energy traversing through the battlefield atmosphere (Shirkey et al, 1995). The visualization is of the scattering and transmission properties of the atmosphere (in terms of cloud and aerosol types, locations, and densities) into the local, spectrally dependent, three-dimensional (3-D) directional radiances and transmittances for a generally 3-D inhomogeneous atmosphere. These quantities are then used to determine, along the line-of-sight for each pixel in the image, the transmission, blurring, and path radiance effects.

WAVES gives the user the ability to modify images to include the effects of weather and atmosphere or to generate images with these effects accurately computed. WAVES performs calculations on two types of images: computer-generated synthetic images and real sensor images. For both types, WAVES uses range-dependent, line-of-sight, transmission, and path radiance effects to modify the images. Also, for the non-real-time or time-averaged modifications, WAVES can include the effects of turbulence through blurring.

The WAVES 3-D grid of atmospheric illumination and propagation information can be used in simulations for testing and evaluation, analysis, planning, training, and research. The 3-D information can be used in constructive simulations, such as JSIMS (http://www.jsims.mil), with some modification and reduction of the amount of information used by the constructive simulation.

In the past, the Electro-Optics Systems Atmospheric Effects Library (EOSAEL) has been the Army standard set of models for computing battlefield effects for EO and acoustic sensors (Wetmore, 1993). This library has been commercialized through the Small Business Innovative Research Contracts program and a cooperative research and development agreement between the Army Research Laboratory and ONTAR Corporation from 1995 to 1998 (Gillespie et al, 1997). This mature product is now available commercially from ONTAR Corporation (www.ontar.com or www.eosael.com), with a friendly user interface or as legacy FORTRAN code through the Defense Modeling and Simulation Resource Repository (a web address will become available summer 1998 through the Defense Modeling and Simulation Office (DMSO) web page) or from TECNET, by contacting Dr. Alan Wetmore (Army Research Laboratory). WAVES is the new generation of atmospheric models available through the Army Research Laboratory. Whenever possible, models for WAVES are adapted from EOSAEL from the line-of-sight point calculations to the newer 3-D nonhomogeneous atmospheric environment. WAVES was conceived and developed under a series of tri-service programs to obtain a complete modeling and simulation of visualization and imaging of the atmospheric environment. WAVES' beginnings may be traced to the Smart Weapons Operability Enhancement (SWOE) Program, through the Target Acquisition Modeling Improvement Program (TAMIP), the DMSO Environmental Effects for Distributed Interactive Simulation (E2DIS) program, and is now under the DMSO Executive Agent for Space and Atmosphere program for the radiometric validation of the Integrated Cloud Scene Simulation (CSSM) Model (Cianciolo, 1996) and the Boundary Layer Illumination and Radiative Balance (BLIRB) model (Zardecki, 1993b).

2. WAVES Overview

The WAVES suite of models predicts illumination and radiance information for a 3-D variable atmosphere as a function of cloud type and amount, including partly cloudy skies at visual and infrared wavelengths. It also predicts EO propagation effects for horizontal and slant paths through the natural atmosphere. The main models in the simulation suite comprise BLIRB, a 3-D spectral radiative transfer code (Zardecki and Davis, 1991; Wetmore and Zardecki, 1993; Zardecki, 1992, 1993a, and 1993b); VIEW, an output database access code for line-of-sight path radiance/transmittance/turbulence evaluations (Zardecki, 1992, 1993a, and 1993b); PixelMod, for image spectral estimation and atmospheric effects modifications of images (Tofsted, 1993, 1994); and ATMOS, a turbulence model for evaluating the vertical profile of the refractive index structure parameter (Beland, 1993; Orgill et al, 1993; Rachele and Tunick, 1994). The WAVES suite has a number of visualization tools being developed for it, which will be described in another volume of this report series. This software is being designed to allow for the visualization of input, intermediate, and output data from the WAVES suite. An example of such data would be a visualization tool that determines the locations of clouds to be placed within the BLIRB space or modeled volume. The turbulence data calculated within ATMOS are then used within the VIEW model to evaluate the so-called receiver coherence diameter (Beland, 1993). This parameter is used to calculate the effects of turbulence blurring of images in the PixelMod code (Tofsted, 1993). The PixelMod code is being rewritten at this time to allow more general system calculations, such as sensor effects. Both VIEW and PixelMod will eventually be part of a WAVES ToolKit, rather than part of the atmospheric propagation calculations.

To perform the range-dependent calculations, WAVES uses line-of-sight radiative transfer calculations that generate the data for image modification. These line-of-sight calculations require a description of the radiation fluxes and extinction throughout the local environment. Radiation fluxes, turbulence parameters, and extinctions are calculated by the first phase of the WAVES models. The real-time image modification is done by PixelMod, which in turn uses databases created by the BLIRB model. The non-real-time image modification is done by the PixelMod program with line-of-sight data created by the VIEW program, based on 3-D databases that are generated by the BLIRB program.

The BLIRB algorithm is a 24-stream (or *n*-stream) discrete ordinates method (DOM) approach to radiative transfer. BLIRB accounts for the scattering in the atmosphere, and MODTRAN is used for the molecular absorption. BLIRB calculates the direct and diffuse illumination at the earth's surface in the spectral range between 0.35 and 40 μm. The model also provides wavelength-dependent radiation fields from the earth's surface to the region up to 12 km above the earth's surface (Zardecki, 1993b).

MODTRAN (Acharya, 1993; Berk, 1989, 1995; Chetwynd, 1996) is an Air Force simulation product, as is the CSSM (Cianciolo, 1996), with which WAVES was designed to be compatible. The region outside the space modeled by WAVES is described by MODTRAN. MODTRAN also provides the molecular extinction needed to complete the atmospheric description of WAVES. A wide variety of natural clouds can be simulated using the full 3-D CSSM output, and that information is interfaced to the WAVES model to provide a 3-D grid of cloud shadow information on the ground. In the near future, a 3-D statistically fluctuating smoke cloud model (COMBIC-STATBIC) will be interfaced to WAVES to provide a more complete atmospheric simulation model (Ayres et al, 1998; O'Brien and Hoock, 1998).

BLIRB was developed for near-earth scenarios, and deals with an area up to 20 km^2 and from ground level up to 5 to 12 km. This allows most cloud-related phenomena to be explored. BLIRB uses an iterative DOM to calculate the direct solar (or lunar) flux, the directional radiances, and the total local extinction and scattering for all points on a grid with typical spacing of 250 m. It performs these calculations for spectral bands defined as in MODTRAN. These calculations allow complex inhomogeneous cloud fields to be used and the resulting complex radiation fields produced. The extension beyond the 1-D vertical profiles available in MODTRAN is essential to realistic modeling of the battlefield. The directional effects allow for realistic changes in the appearance of scenes as the observer rotates; the inhomogeneity allows for clouds to engulf the observer or target, or pass between them, all in a self-consistent, radiometrically correct manner.

BLIRB requires, as input, optical properties of the atmospheric medium calculated from MODTRAN4 and the EOSAEL PFNDAT (Tofsted et al, 1997) aerosol phase function database. MODTRAN4 also provides the solar insolation at the top of the modeled volume, for multiple paths in terms of spectrally dependent direct and diffuse terms. Calculations are separated into different modules, to make the WAVES suite as flexible as possible. To maximize the use of each BLIRB calculation, the input scenarios to BLIRB should represent a general class of weather. BLIRB then calculates the 3-D database of wavelength-dependent extinction, scattering, and directional radiances. This information is used by VIEW to calculate nonhomogeneous range-dependent path radiance and transmittance, integrating along the multiple paths of interest. VIEW may also use a subset of the wavelength range of BLIRB. The path of interest is defined by the location of the observer and the viewing elevation and azimuth angles. The visualizer, or ToolKit, is used to simulate what those data look like at any of the intermediate stages of calculations.

The result of the BLIRB model is a database of extinction, scattering, and directional radiances that depend on the wavelength and position in 3-D space. These values are used for the viewing and imaging tools as they project lines-of-sight through space from the observing sensor to the elements that make up the scene.

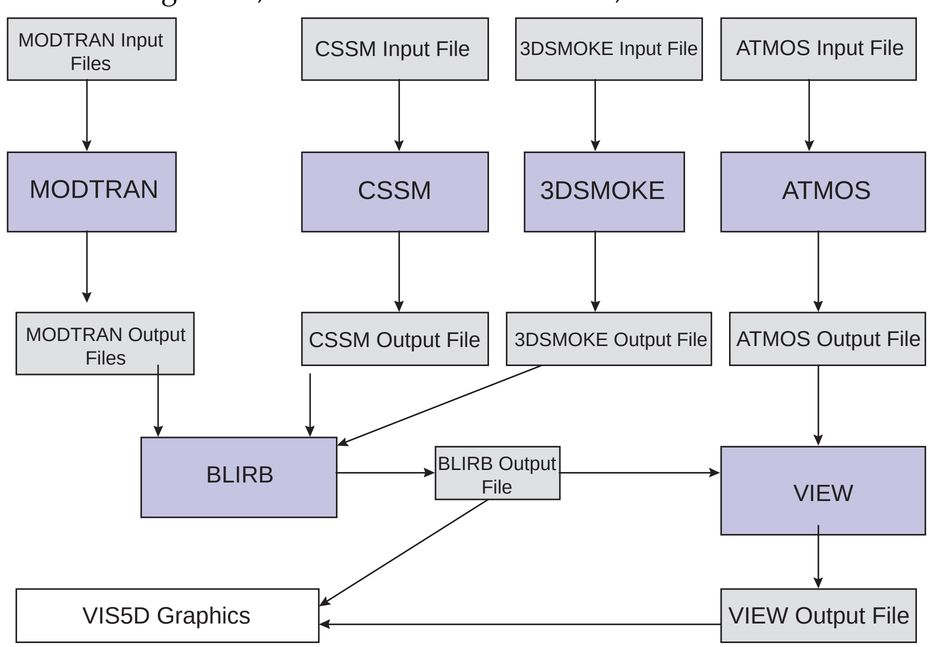
ATMOS is used to calculate the vertical profile of the refractive index structure parameter, C_n^2, assuming horizontal homogeneity. This turbulence calculation is made using easily obtainable meteorological parameters (Rachele and Tunick, 1994). The refractive index structure parameter is used in a modulation transfer function (MTF) that is folded into the propagation calculations to give time-averaged effects, or blurring, from turbulence. Real-time fluctuations due to turbulence are not computed with this model.

VIEW computes the transmittance, path radiance, turbulent coherence diameter characterizing blurring due to optical turbulence, and parameters characterizing aerosol forward scattering for a set of observer lines of sight specified by the user. Each of these range-dependent parameters are computed by integrating along the LOS. VIEW integrates along each specified line of sight to determine the range-dependent effects of interest (Zardecki, 1993b). These parameters are subsequently applied in PixelMod.

PixelMod applies the effects of forward scattering, path radiance, turbulence, and transmission to background objects that are within the image field by computing the image modification due to the atmosphere on a pixel-by-pixel basis (Tofsted, 1993). PixelMod simulates wavelength-dependent effects by estimating the spectral content of each pixel on a color image, applying spectrally dependent atmospheric effects to each spectral band, and reconstructing an output color image based on weighted responses of the simulated receiver (Tofsted, 1994).

Figure 1 is a logical connection diagram between the different modules currently in the WAVES suite of atmospheric effects models. Lavender boxes indicate executables, gray boxes indicate data or files, and the white box is the graphics toolbox. The PixelMod code uses the output from the VIEW model. It is not shown in this diagram because it is being written into a more general, useful form. Other models, such as the 3DSMOKE

Figure 1. Logical connection diagram for WAVES.



model based on COMBIC-STATBIC, will soon become part of this suite. As WAVES evolves, the physics models will remain at the core of the suite, and VIEW and PixelMod will become part of the ToolKit that will accompany the WAVES suite.

The general description of the currently used radiative transfer calculation process has been reported by Wetmore and Zardecki (1993). The general physics in the turbulence calculations in ATMOS are described by Rachele and Tunick (1994). Technical documentation and a reference guide are planned as part of the documentation for the WAVES suite. This documentation is described later in this report.

The image conversion process starts with the analysis of the image and conversion, pixel-by-pixel, to a spectrally resolved element. This allows the creation of many spectral band images similar to the three RGB images from a common video source. Since each pixel represents a point in a 3-D geometry, based on observer position and look direction and range to a given pixel, the appropriate data from BLIRB can be applied to modifying the pixel's spectral content. The final step is to re-combine the spectrally resolved information into the three RGB signals for display. Tofsted describes both the general image processing approach (1993) and the spectral estimation process (1994).

A project to develop data visualization for the various stages of WAVES data is under way at this time. Various nonproprietary tools, such as VIS5D (http://iris.ssec.wisc.edu/vis5d.html), GrADs (http://grads.iges.org/grads/head.html), and TOSL-TOEM (http://www7180.nrlssc.navy.mil/homepages/TOSL/TOSL.html) are being evaluated for use with WAVES data. These visualization tools would allow the WAVES user to easily view information that moves from one part of WAVES to another. Another ongoing effort is the object-oriented model wrappers that are being developed for WAVES. These wrappers will allow users to incorporate all or portions of WAVES (and MODTRAN/CSSM) into simulations that require High-Level Architecture (HLA) or Distributed Interactive Simulation (DIS) compliance (Army Research Laboratory Broad Agency Announcement (BAA) contract DAAL01-97-C-0152). Figure 2 shows how the various modules in WAVES and the Air Force models, MODTRAN and CSSM, will interact in an HLA environment. This figure is taken from the WAVES milestone document by Seablom (1998).

WAVES is being developed so that there is easy interchange of models; that is, we can easily substitute a new turbulence model for ATMOS or radiative transfer model for BLIRB, if we have another model that works better for a specific application. Input/output for all models is described in the user's manual so that such an interchange is easy.

Many portions of these models have been scientifically evaluated, in comparisons to other models and comparisons to data. Another volume in this series of reports is devoted to a discussion of the model evaluations that have been conducted thus far (Wells, 1995, 1996; Gillespie et al, 1994; Tofsted et al, 1995; Wetmore, 1997; Mozer, 1997).

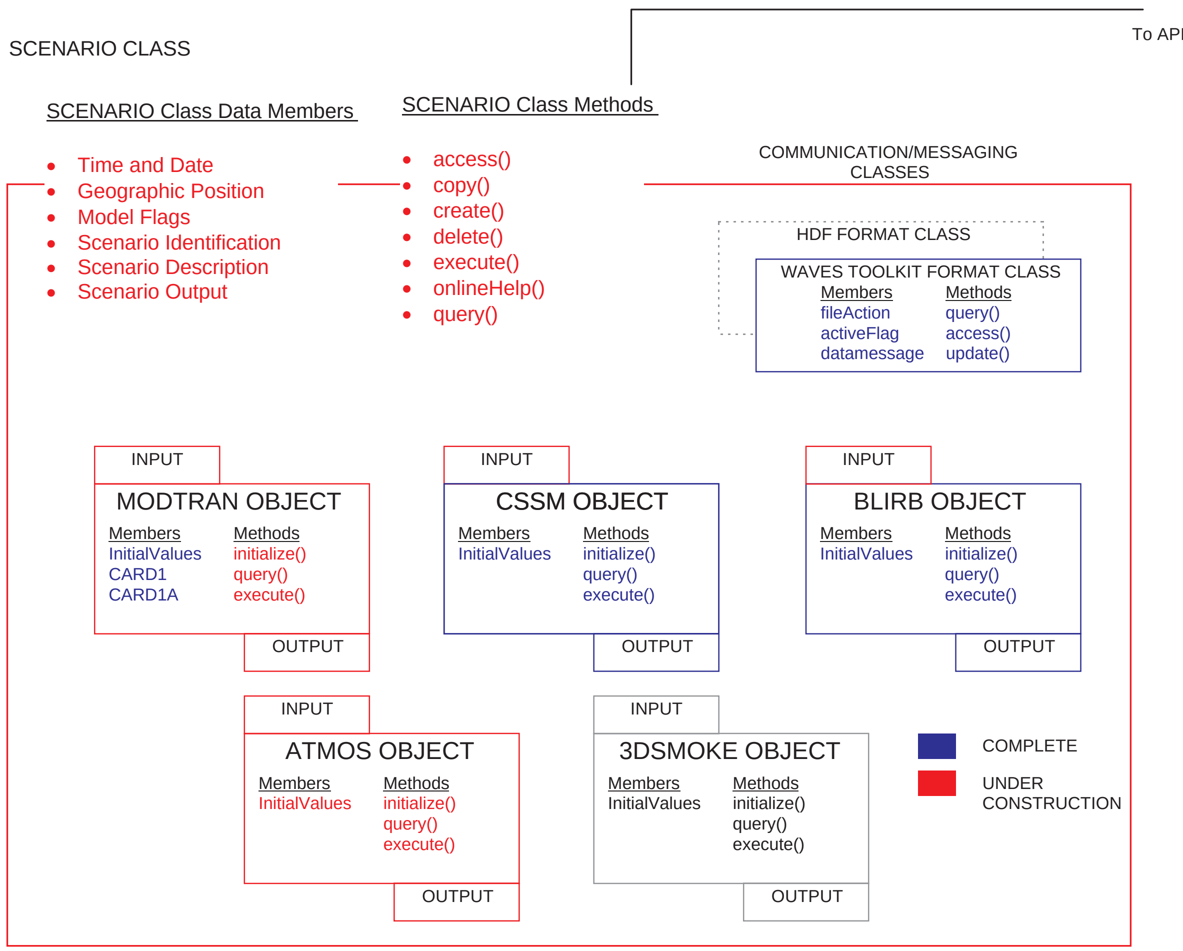


Figure 2. WAVES HLA structure, which can be run from programs such as TAOS through applications programming interface or graphical user interface.

3. Image Modification and Data Visualization

Images may be modified with the effects described in section 2 with the use of the following algorithm:

$$S_{ij} = T_{ij}\left(I_{ij} + \sum_{\substack{k=l-n \\ l=j-n}}^{\substack{i+n \\ j+n}} K_{kl} I_{kl} \right) + P_{ij} \ ,$$

where S_{ij} is the brightness of the sensor pixel, T_{ij} is the transmission coefficient from image pixel to sensor pixel, I_{ij} is the brightness of the image pixel, K_{kl} is the blurring kernel of size $2n + 1$, and P_{ij} is the brightness of the path radiance from image pixel to sensor.

An example of illumination values being visualized is shown in figure 3. This figure depicts the intensity of illumination, at the surface with some cumulus clouds in the volume of interest. The red indicates more intense illumination, and the blue indicates cloud shadows or less intense illumination. The change in illumination is a result of the intervening atmosphere and the clouds. The ToolKit allows one to look at illumination of slices through the atmosphere, the various streams of radiation, slices of the clouds, and any of the quantities handled by WAVES.

WAVES has been used to modify images that include scenarios with a horizontal path length, slant path scenarios, and vertical viewing scenarios. An example of a vertical viewing scenario is shown in figure 4. The images, downloaded from the LandSat satellite commercial web page, are of a building in Vienna, Austria. Figure 4a is the untreated, clear

Figure 3. Illumination visualization of volume of atmosphere.

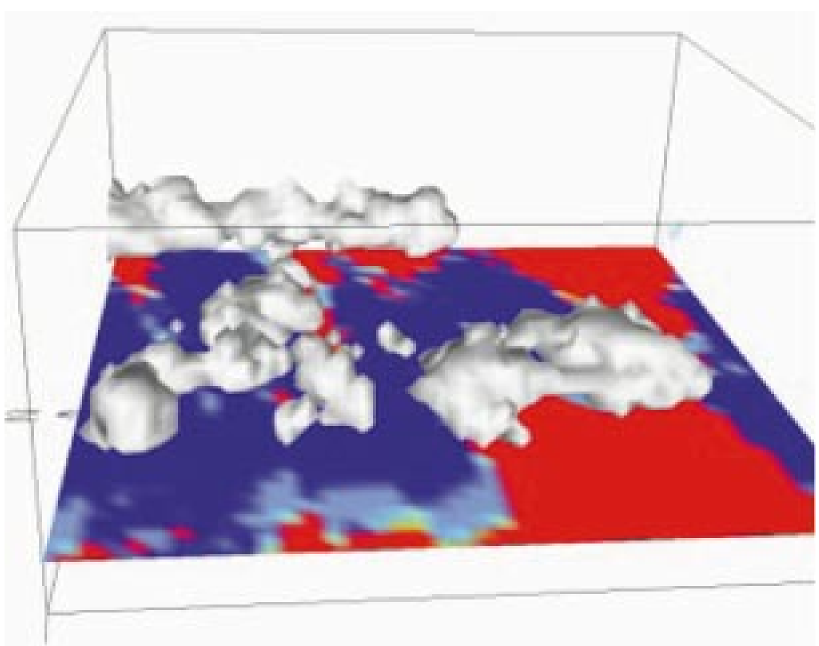


Figure 4. Vertical viewing scenario of Vienna, Austria: (a) clear LandSat image, (b) summer urban haze aerosol inserted over image, and (c) thin stratus cloud inserted over image.

(a)

(b)

(c)

image. We have taken that image and imposed a summer haze aerosol for figure 4b, and a thin stratus cloud in figure 4c. Notice that the red cars in the parking lot retain their red color better than the blue objects in the scenes with the aerosols or thin cloud. This is what one would expect from scattering by aerosols. The detail in these images is better preserved when viewed on a computer screen than on a printed page or viewgraph.

That an image may be modified to include additional effects means that it can be used as a planning tool for various contingencies, as an evaluation tool for testing and evaluation, and as an engineering tool for development. It also means that we may be able to remove these atmospheric effects from degraded images.

4. Past and Future Perspectives

WAVES research initiatives in the past have included development of the *n*-stream model (improvement over the original two-stream model), albedo effects, flares, enhanced aerosol choices, and the evaluation of the multiple scattering routine. Two past efforts to evaluate WAVES were a comparison of several WAVES scenarios to corresponding Monte Carlo calculations with a documented Monte Carlo model (Tofsted et al, 1995; Wells, 1995, 1996). The other projects used scene metrics and statistics in an attempt to quantify physical properties depicted in a scene (Gillespie et al, 1995; Wetmore et al, 1997).

Current research projects include an integration and end-to-end evaluation with integrated CSSM-BLIRB models (Mozer et al, 1997; Wetmore et al, 1997). This project includes the development of the appropriate hooks with the WAVES suite, including all cloud types modeled by CSSM, and the use of that input to appropriately calculate the effect of the atmosphere on electromagnetic radiation. As mentioned above, the integrated model is being experimentally evaluated during an ongoing Army/Air Force two-year program, funded by the Executive Agent for Space and Atmosphere. Another part of this work has been to upgrade the absorption calculations currently done by LOWTRAN to those done by MODTRAN.

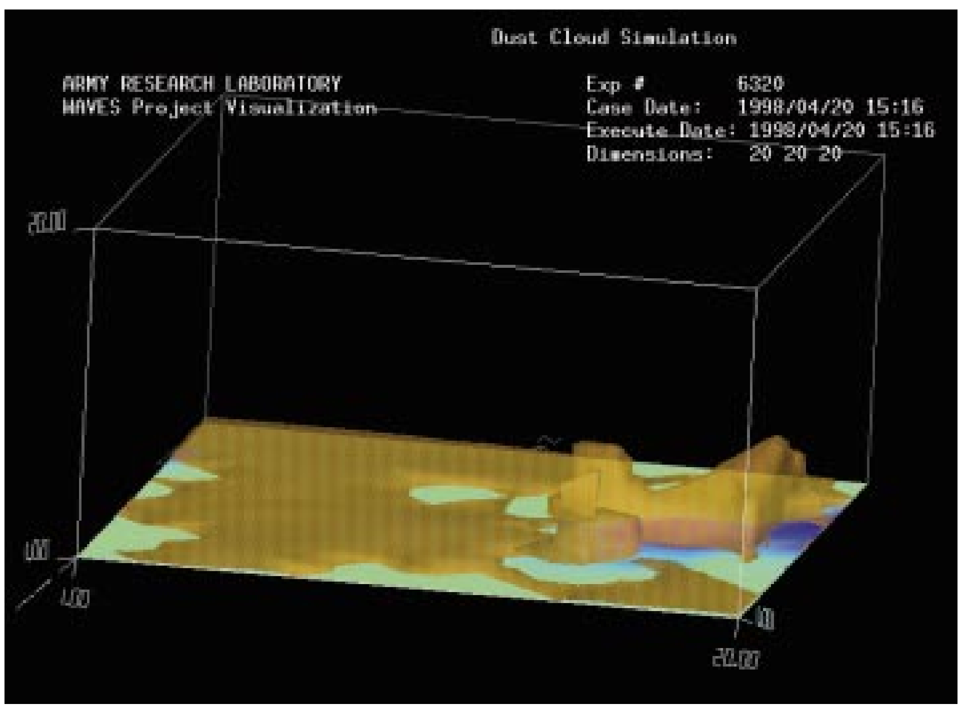
Another project started this year, Smoke Clouds for Simulation, funded by CHSSI (Common HPC Software Support Initiative), is the integration of WAVES and the 3-D textured smoke model with scaleable architecture. The smoke model is based on the EOSAEL COMBIC model (Ayres et al, 1998) and a texture model developed by ARL called STATBIC (Hoock and Giever, 1994; O'Brien and Hoock, 1998). Output from the STATBIC-COMBIC model is shown in figure 5a, and output from the smooth plume model in COMBIC is shown figure 5b. We can use the same architecture to incorporate smoke as we have used for the clouds or aerosols. Once cloud plumes can be computed and textured, we should be able to regularly depict smokes with our WAVES suite. This will create a robust smoke model for use with total atmospheric simulations. Since much of the coding for these algorithms is legacy FORTRAN, innovative computational techniques and high-performance computing techniques such as scaleable architecture are speeding up computation significantly.

We have preliminary results for a dust cloud in an image similar to the one shown in figure 3. In figure 3, the cloud is a water vapor cloud. Similar modeling techniques give us the image in figure 6. The cloud is a low-altitude dust cloud generated by a fractal model that is not tuned for dust or military smokes. The calculations for this image generation are not robust as yet, but are planned to be so in the future. There is a layer of dust on the ground in figure 6. Notice that the shadow under this cloud is not as dark as for water clouds, because the cloud is not as thick. (Note: the scale of illumination is different in fig. 3 and 6.) Work in the near future will focus in part on building better smoke and dust cloud capabilities.

Future directions include consideration of polarization effects and an expanded wavelength range. Longer-range projects include integration of the effects of wind, transport and diffusion, atmospheric forecast data, and a turbulence model that can provide realistic scintillation effects for simulation.

Figure 5. COMBIC and COMBIC-STATBIC smoke plume images.

Figure 6. Dust cloud in virtual environment.



5. Model Suite Documentation Outline

The WAVES software is being documented through a series of Army Research Laboratory technical reports. The general volumes planned are outlined below, with short commentary on the contents of each volume.

Volume 1 **WAVES Overview**

This volume describes the general overview, capabilities, and philosophy behind the WAVES suite. It also summarizes the other documentation that is (or will be) available for WAVES.

Volume 2 **User's Guide**

This volume describes the use of the WAVES models and guides both the novice and experienced user through the many inputs and outputs of the various models.

Volume 3 **Sample Scenarios**

Sample scenarios are published in this volume, which may be updated periodically. These sample scenarios can be used to test the code for extreme conditions.

Volume 4 **BLIRB Technical Documentation**

The technical documentation describes the physics of the radiative transfer model in BLIRB, as well as the approximations and shortcomings of the model. This information can be found in the Zardecki references (1991, 1992, 1993a, 1993b).

Volume 5 **ATMOS Technical Documentation**

This report is technically very similar to the EOSAEL CN2MAR report published as part of the EOSAEL series of technical reports (Tunick, 1998).

Volume 6 **3DSMOKE Technical Documentation**

The 3DSMOKE model is a direct adaptation of the EOSAEL COMBIC model combined with the STATBIC texture model to provide the inhomogeneous smokes.

Volume 7 **WAVES ToolKit**

This volume describes utilities built to assist in the use of WAVES. Utilities are important to the management of the information that must move between the various modules of WAVES (Seablom, 1998).

Volume 8 **Model Evaluations**

This volume is a compilation of several model evaluations done on the models in WAVES, and on WAVES as a suite of models. It may contain several sub-volumes or parts. This information is already contained in several reports and papers (Gillepsie et al, 1995; Mozer et al, 1997; Wells, 1995, 1996; Wetmore, 1997; Zardecki, 1992, 1993a).

6. Summary

In the past the EOSAEL models were the standard for calculations of transmission through the atmosphere, smoke, and dust (Wetmore, 1993). A need is emerging for atmospheric effects modeling, as EOSAEL becomes a commercialized product. To this end, the WAVES suite was designated as an ideal software product in which to include small-scale smoke simulation. WAVES is part of a tri-services effort that provides an atmospheric simulation from MODTRAN calculations for large-scale extinction, CSSM calculations for natural cloud effects, BLIRB calculations for radiative transfer, and ATMOS calculations for blurring due to turbulence. A new version of COMBIC that integrates fractal texturing (STATBIC) is being developed for WAVES (Pearson, 1998; O'Brien and Hoock, 1998). It is expected that WAVES (Wetmore, 1998) will become a standard environment for radiative transfer calculations for the Army in the next three to five years.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
September 1998

3. REPORT TYPE AND DATES COVERED
Summary 1995–1998

4. TITLE AND SUBTITLE
Weather and Atmospheric Effects for Simulation
Volume 1: WAVES98 Suite Overview

5. FUNDING NUMBERS
DA PR: B53A
PE: 61102A

6. AUTHOR(S)
Patti Gillespie, Alan Wetmore, and David Ligon

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
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2800 Powder Mill Road
Adelphi, MD 20783-1197

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-1721-1

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
2800 Powder Mill Road
Adelphi, MD 20783-1197

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
ARL PR: 8FEJ60
AMS code: 61110253A11

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
The Weather and Atmospheric Effects for Simulation (WAVES) suite of models calculates and visualizes environmental effects due to natural clouds, haze, and fog. These models determine the illumination through multiple inhomogeneous cloud layers and the resulting radiance field. Other effects calculated with these models are forward scattering and optical turbulence. WAVES comprises BLIRB (the Boundary Layer Illumination and Radiative Balance model), ATMOS (a turbulence model), PixelMod (an image modifier), and VIEW (a viewing geometry model). Other models will be added to this suite in the future. A model being developed for the near future is 3DSMOKE, which is based on the EOSAEL (Electro-Optics Systems Atmospheric Effects Library) COMBIC (Combined Obscuration Model for Battlefield-Induced Contaminants) model. A ToolKit is being developed to aid in the viewing of input, output, and intermediate data within WAVES. This suite of models can simulate a scene or can be used to modify an image. This overview discusses the scope of this modeling suite, and maps the other documentation for the suite.

14. SUBJECT TERMS
Atmosphere, models, simulation, visualization, propagation, extinction, radiative transfer, turbulence, smoke, dust, aerosols, electro-optical, BLIRB, ATMOS, VIEW, PixelMod, Vis5D

15. NUMBER OF PAGES
27

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102